The influence of barefoot and shod running on Triceps-surae muscle strain characteristics

Sinclair, Jonathan Kenneth, Cole, Tom and Richards, Jim

The Foot and Ankle Online Journal
Official Publication of the International Foot & Ankle Foundation
faoj.com / ISSN 1941-6806

The influence of barefoot and shod running on Triceps surae muscle strain characteristics

by Sinclair J[1*], Cole T[2], Richards J[2]

The Foot and Ankle Online Journal 9 (1): 4

The aim of the current investigation was to determine the effects of barefoot and shod running on the kinematics of the Triceps-Surae muscle group. Twelve male participants ran at 4.0 m.s^{-1} (± 5%) in both barefoot and shod conditions. Kinematics were measured using an eight-camera motion analysis system. Muscle kinematics from the lateral Gastrocnemius, medial Gastrocnemius and Soleus were obtained using musculoskeletal modelling software (Opensim v3.2). The results showed that muscle strain for the lateral Gastrocnemius (barefoot = 1.10 & shod = 0.33 %), medial Gastrocnemius (barefoot = 1.07 & shod = 0.32 %) and Soleus (barefoot = 3.43 & shod = 2.18 %) were significantly larger for the barefoot condition. Given the proposed association between the extent of muscle strain and the etiology of chronic muscle strain pathologies, the current investigation shows that running barefoot may place runners at greater risk from Triceps-Surae strain injuries.

Key words: Biomechanics, barefoot, shod, Triceps-Surae.

Engaging in recreational and competitive distance running has been shown to provide a number of health benefits [1]. Despite this runners are highly susceptible to chronic injuries [2], with an occurrence rate of around 80 % over the course of one year [3]. A large number of strategies have been investigated in biomechanical research with the specific aim of attenuating the risk of running injuries.

One such conservative strategy is to choose running shoes with appropriate mechanical characteristics; the properties of running shoes have been proposed as a mechanism by which chronic injuries can be controlled [4]. Recently barefoot running has been the focus of much attention in biomechanics research.

1 - Centre for Applied Sport Exercise and Nutritional Sciences, School of Sport & Wellbeing, College of Health & Wellbeing, University of Central Lancashire, UK.
2 - Allied Health Research Unit, School of Health, College of Health & Wellbeing, University of Central Lancashire, UK.
* Correspondence: Dr. Jonathan Sinclair, jksinclair@uclan.ac.uk

The popularity and attention paid to barefoot footwear is due the proposition that running barefoot may be able to reduce the incidence of chronic running injuries [5, 6].

The findings from biomechanical research into the kinetics and kinematics of running barefoot in comparison to shod have been equivocal. Sinclair et al. [7] examined the effects of barefoot and shod running on kinetics, kinematics and tibial accelerations during the stance phase. Their kinematic observations showed that the ankle was significantly more plantarflexed at footstrike in the barefoot condition. In addition it was also shown the running barefoot was associated with significantly greater tibial accelerations and vertical rates of loading. Sinclair et al. [8] similarly investigated the effects of barefoot and shod conditions on running kinetics and kinematics. Their kinematic findings showed that barefoot running was associated with a more plantarflexed ankle position at footstrike and also a greater peak eversion angle. The kinetic findings indicated that barefoot running demonstrated a significantly greater vertical rate of loading. When comparing the kinetics and sagittal plane kinematics of running barefoot and shod, Lieberman et al [5] demonstrated firstly that the ankle was significantly more plantarflexed at footstrike in the barefoot condition. However, their kinetic observations showed that the vertical rate of loading was larger when running with shoes. Similarly, Squadrone & Gallozzi, [9] showed that running barefoot was associated with increased plantarflexion at footstrike but with subsequent reductions in peak vertical impact forces.

In addition, with the development more accurate musculoskeletal models more recent research has been able to investigate the loads experienced by specific musculoskeletal structures. Bonacci et al, [10] showed that running barefoot was associated with significant reductions in patellofemoral loading in comparison to shod. Sinclair, [11] similarly demonstrated that patellofemoral loading was significantly reduced when running barefoot but that running without shoes mediated subsequent increases in the loads borne by the Achilles tendon. Finally, Sinclair et al, [12] investigated the effects of barefoot and shod running on limb and joint stiffness characteristics during the stance phase. They showed that limb and knee stiffness were greater when running barefoot but that ankle stiffness was greater when running shod.

There is currently a paucity of biomechanical research investigating muscle mechanics during barefoot and shod running. Sinclair et al, [13] investigated the effects of barefoot and shod running on lower limb muscle forces during the stance phase of running. Their observations showed that peak forces from the Rectus femoris, Vastus medialis, Vastus lateralis and Tibialis anterior were significantly larger in the shod condition whereas Gastrocnemius forces were significantly larger during barefoot running. Similarly, Sinclair, [14] studied the effects of running barefoot and shod on peak and mean foot muscle forces. The findings confirmed that peak and mean forces from the Flexor digitorum longus, Flexor hallucis longus, Peroneus longus muscles were significantly larger when running barefoot, whereas peak and average forces of the Extensor digitorum longus and Extensor hallucis longus muscles were significantly larger when running shod.

There has yet to be any published research investigating Triceps Surae muscle mechanics during barefoot and shod running. Anecdotal evidence of calf pain and stiffness has been reported by runners who seek to conduct their training without shoes. Furthermore, the prospective investigation of Altman & Davis [15] showed that calf injuries may be more prominent in barefoot runners in comparison to those who train shod. This indicates that an investigation into the mechanics of the Tricep-surae (calf) muscle group during barefoot and shod running would be of both practical and clinical significance to both clinicians and runners themselves.

Therefore the aim of the current investigation was to determine the effects of barefoot and shod running on the kinematics of the Triceps Surae muscle group. A study of this nature may aid our understanding of muscle function during barefoot running. The current work tests the hypothesis that the magnitude of strain experienced by the Triceps Surae muscles will be significantly larger when running barefoot.

Methods

Participants

Twelve male runners (age 23.58 ± 2.88 years, height 1.77 ± 0.10 cm and body mass 79.40 ± 5.87 kg) volunteered to take part in this study. All runners were free from musculoskeletal pathology at the time of data collection. Participants provided written informed consent in accordance with the principles outlined in the Declaration of Helsinki. Each runner was considered to be exhibit a natural rearfoot strike pattern as they exhibited an impact peak in their vertical ground reaction force curve when wearing conventional footwear. The procedure was approved by the University of Central Lancashire ethical committee.

Procedure

Participants ran at a velocity of 4.0 m.s^{-1} ±5%, striking an embedded force platform (Kistler, Kistler Instruments Ltd., Alton, Hampshire) with their right (dominant) foot [16]. The velocity of running was monitored using infrared timing gates (Newtest, Oy Koulukatu, Finland). The stance phase was defined as the duration over which 20 N or greater of vertical force was applied to the force platform [17]. All runners completed five successful trials in each footwear condition.

Kinematic information was captured at 250 Hz using an eight camera optoelectric motion analysis system (Qualisys™ Medical AB, Goteburg, Sweden). To define the anatomical frames of the trunk, pelvis, thighs, shanks and feet retroreflective markers were placed at the C7, T12 and xiphoid process landmarks and also positioned bilaterally onto the acromion process, iliac crest, anterior superior iliac spine, posterior super iliac spine, medial and lateral malleoli, medial and lateral femoral epicondyles and greater trochanter. Carbon-fiber tracking clusters comprising of four non-linear retroreflective markers were positioned bilaterally onto the thigh and shank segments. Static calibration trials were obtained with the participant in the anatomical position in order for the positions of the anatomical markers to be referenced in relation to the tracking clusters/markers.

Data processing

Marker trajectories were filtered 12 Hz using a low pass Butterworth 4th order zero-lag filter and analyzed using Visual 3D (C-Motion, Germantown, MD, USA. All information was normalized to 100 % of the stance phase. For the current study angular kinematics of the ankle joint were examined. Kinematic measures from the ankle were extracted for statistical analysis were 1) angle at footstrike and 2) relative peak range of motion from footstrike to peak angle.

OpenSim software was used to quantify muscle-tendon lengths during the stance phase of running [18]. Muscle kinematics were quantified using the gait2392 model using OpenSim v3.2. This model corresponds to the eight segments exported from Visual 3D and features ninety two muscles, eighty six of which are centered around the lower extremities and six are associated with the pelvis and trunk. The muscle properties were modelled using the Hill recommendations based on the associations between force-velocity-length [19]. These muscle properties were then scaled based on each participant's height and body mass based on the recommendations of Delp et al, [20]. Muscle-tendon lengths are determined by the positions of their proximal and distal muscles muscle origins. The muscle–tendon units which were evaluated as part of the current research were the lateral Gastrocnemius, medial Gastrocnemius, and Soleus. Muscle kinematic parameters that were extracted for statistical analysis were 1) eccentric strain (representative of the maximum increase in muscle length divided by the length at footstrike and 2) peak lengthening velocity.

In addition to this we also estimated the total muscle strain experienced per mile (% x mile) by multiplying the muscle strain magnitude by the number of steps required to complete one mile. The number of steps required to complete one mile was calculated using the step length. Step length was obtained by taking the difference in the horizontal position of the foot between the right and left legs at footstrike [21, 22].

Statistical analyses

Descriptive statistics (means, standard deviations and 95% confidence intervals) were obtained for each footwear condition. Shapiro-Wilk tests were used to screen the data for normality. Footwear mediated differences in foot muscle kinetics were examined using paired samples t-tests. All statistical actions were conducted using SPSS v22.0 (SPSS Inc, Chicago, USA).

Results

Figures 1-3 and table 1 show ankle joint and muscle kinematics as a function of barefoot and shod running conditions. The results show that the different running conditions significantly influence both joint and muscle kinematics.

Ankle kinematics

The ankle was found to be significantly ($t_{(11)} = 4.51$, $p<0.05$) more plantarflexed at footstrike in the barefoot conditions in comparison to shod. Furthermore, the relative range of motion was found to be significantly ($t_{(11)} = 4.08$, $p<0.05$) greater when running barefoot in comparison to shod (Figure 1).

Muscle kinematics

For the lateral Gastrocnemius muscle running barefoot was associated with significantly ($t_{(11)} = 2.81$, $p<0.05$) larger muscles strain in comparison to shod running (Figure 2a; Table 1). In addition when running barefoot the lateral Gastrocnemius exhibited a significantly ($t_{(11)} = 2.37$, $p<0.05$) greater lengthening velocity than during shod running (Figure 2a; Table 1). Finally barefoot running was associated with a significantly ($t_{(11)}$ = 2.81, $p<0.05$) greater strain experienced per mile (Table 1).

For the medial Gastrocnemius muscle running barefoot was associated with significantly ($t_{(11)}$ = 2.79, $p<0.05$) larger muscle strain in comparison to shod running (Figure 2b; Table 1). In addition when running barefoot the medial Gastrocnemius exhibited a significantly ($t_{(11)}$ = 2.39, $p<0.05$) greater lengthening velocity than during shod running (Figure 3b; Table 1). Finally barefoot running was associated with a significantly ($t_{(11)}$ = 2.83, $p<0.05$) greater strain experienced per mile (Table 1).

For the Soleus muscle running barefoot was associated with significantly ($t_{(11)}$ = 3.79, $p<0.05$) larger muscle strain in comparison to shod running (Figure 2c; Table 1). In addition when running barefoot the Soleus exhibited a significantly ($t_{(11)}$ = 2.69, $p<0.05$) greater lengthening velocity than during shod running (Figure 3c; Table 1). Finally barefoot running was associated with a significantly ($t_{(11)}$ = 3.93, $p<0.05$) greater strain experienced per mile (Table 1).

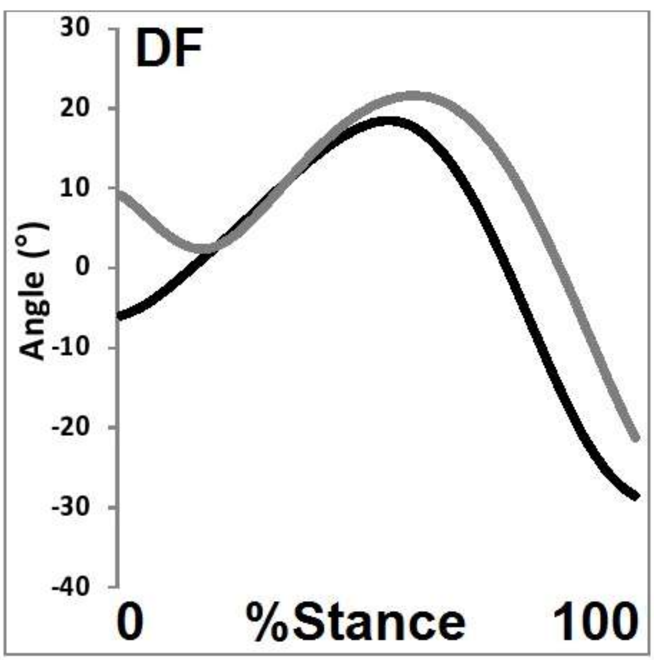

Figure 1 Sagittal ankle kinematics as a function of barefoot and shod conditions (black = barefoot and grey = shod) (DF = dorsiflexion).

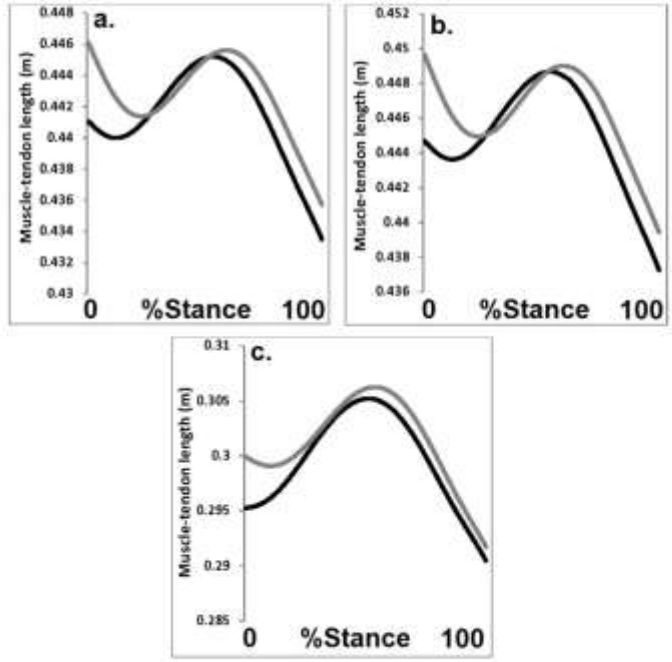

Figure 2 Tirceps Surae muscle kinematics as a function of barefoot and shod conditions (black = barefoot and grey = shod) (a. = lateral Gastrocnemius, b. = medial Gastrocnemius, c. = Soleus).

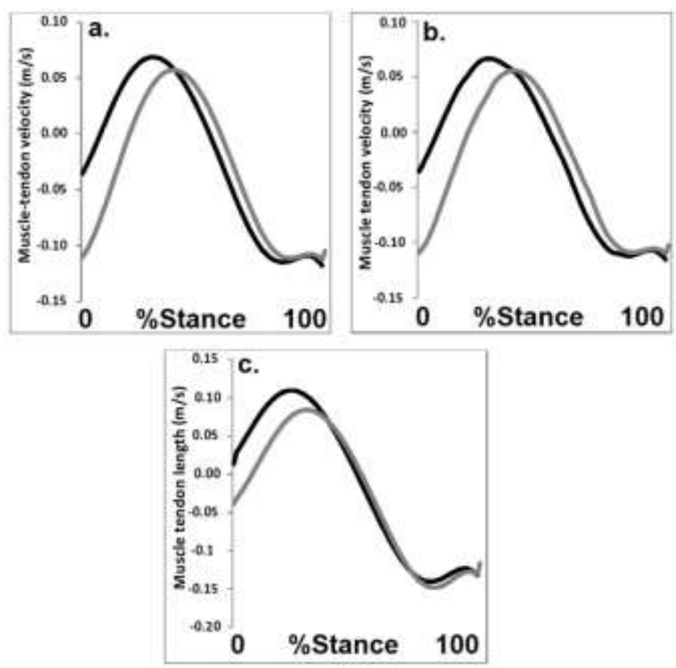

Figure 3 Tirceps Surae muscle velocities as a function of barefoot and shod conditions (black = barefoot and grey = shod) (a. = lateral Gastrocnemius, b. = medial Gastrocnemius, c. = Soleus).

	Barefoot			Shod		
	Mean	*SD*	*95% CI*	*Mean*	*SD*	*95% CI*
Lateral Gastrocnemius Strain (%)	1.10	0.88	0.54 – 1.66	0.33	0.68	0.10 – 0.76
Lateral Gastrocnemius velocity (m/s)	0.08	0.04	0.05 – 0.10	0.06	0.03	0.04 – 0.08
Lateral Gastrocnemius Strain per mile (%x mile)	769.45	533.14	367.17 – 1171.73	234.49	399.94	-83.57 – 552.17
Medial Gastrocnemius Strain (%)	1.07	0.86	0.52 – 1.61	0.32	0.66	-1.05 – 0.74
Medial Gastrocnemius velocity (m/s)	0.07	0.04	0.05 – 0.10	0.06	0.03	0.42 – 0.77
Medial Gastrocnemius Strain per mile (%x mile)	743.29	516.03	351.88 – 1134.70	226.49	387.98	-83.55 – 536.55
Soleus Strain (%)	3.43	1.65	2.38 – 4.48	2.18	0.94	1.58 – 2.78
Soleus velocity (m/s)	0.11	0.05	0.08 – 0.15	0.09	0.03	0.06 – 0.11
Soleus Strain per mile (%x mile)	2374.41	1032.62	1591.15 – 3157.48	1414.26	623.58	998.72 – 1829.79

Table 1 Triceps Surae muscle kinematics (Means, SD's & 95% CI's) as a function of barefoot and shod conditions.

Discussion

The aim of the current investigation was to quantify the effects of barefoot and shod running on Triceps Surae muscle kinematics. To the authors knowledge this represents the first comparative analysis of Triceps Surae mechanics when running in different footwear.

The first key observation from the current paper is that ankle was shown to be significantly plantarflexed at footstrike in the barefoot condition in comparison to running shod. This indicates that runners modified their footstrike pattern and adopted a non-rearfoot strike when running barefoot. This finding concurs with the observations of Squadrone & Gallozzi, [9], Lieberman et al, [5] and Sinclair et al, [7, 8] who each showed a more plantarflexed ankle position when wearing running barefoot. It proposed that this finding relates to the absence of shoe cushioning when running barefoot. Runners adopt a non-rearfoot strike pattern in order to compensate for the lack of a shoe midsole and attenuate the loads experienced by the musculoskeletal system [5]. The first key finding from the current work is that strain magnitude and velocity in each of the three muscles associated with the Triceps-Surae was significantly larger in the barefoot condition in comparison to shod. This observation supports our original hypothesis and may have clinical significance. Muscle strains occur as a function of excessive muscle lengthening during periods of eccentric muscle lengthening [23]. The findings from the current investigation therefore support the proposition of Altman & Davis, [15] in that running barefoot appears to place runners at increased risk from Triceps-Surae strain injuries.

It is proposed that these observations relate to the change in footstrike pattern and increased range of motion mediated by running without shoes. The Triceps-Surae muscles insert distally into the Achilles tendon insertion and proximally at the posterior aspects of the tibia/ femur. Therefore the increased plantar flexion at footstrike observed when running barefoot means that the muscles are in a shortened position compared shod running. This in conjunction with the increased dorsiflexion range of motion at the ankle means that the Triceps-Surae must lengthen to a greater extent given the anterior translation of the proximal muscle insertion points. This finding therefore suggests that whilst the non-rearfoot strike pattern associated with barefoot running may reduce the load experienced by the patellofemoral joint [10, 11] and also vertical rate of loading [5,9] it may be at the expense of increased Triceps-Surae strain.

The findings in relation to muscle strains from the current investigation can be further contextualized taking into account the increased number of steps required to complete one mile when running barefoot. This led to further increases in the amount of muscle strain experienced per mile, over and above those reported per footfall when participants ran barefoot. Therefore, whilst the amount of strain experienced per footfall is relatively small when contrasted against muscle strains shown in other sports [24], because running represents a cyclical activity which involves multiple footfalls the cumulative strain is high. This observation further supports the notion that running barefoot may enhance the likelihood of experiencing a chronic muscle strain injury at the Triceps-Surae.

In conclusion, although differences in the effects of barefoot running have been examined extensively, the current knowledge regarding the differences in Triceps-Surae kinematics between barefoot and shod running is limited. The present investigation therefore adds to the current knowledge by providing a comprehensive evaluation of Triceps-Surae muscle kinematic parameters when running in barefoot and shod conditions. On the basis muscle strain parameters were significantly greater when running barefoot; the findings from the current investigation indicate that barefoot running may place runners at increases risk from chronic Triceps-Surae muscle strain injuries in comparison to running shod.

References

1. Schnohr P, O'Keefe JH, Marott JL, Lange P, Jensen GB. Dose of jogging and long-term mortality: the Copenhagen City Heart Study. Journal of the American College of Cardiology 2015; 65: 411-419. (PubMed)
2. Taunton JE, Clement DB, McNicol K. Plantar fasciitis in runners. Canadian Journal of Applied Sport Sciences 1982; 7: 41-44. (PubMed)
3. van Gent R, Siem DD, van Middelkoop M, van Os TA, Bierma-Zeinstra SS, Koes, BB. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. British Journal of Sports Medicine 2007: 41: 469-480. (PubMed)
4. Shorten, MA. Running shoe design: protection and performance. pp 159-169 in Marathon Medicine (Ed. D. Tunstall Pedoe). 2000; London, Royal Society of Medicine.
5. Lieberman DE, Venkadesan M, Werbel WA, Daoud AI, D'Andrea S, Davis IS, et al. Foot strike patterns and collision forces in habitually barefoot versus shod runners. Nature; 2010; 463: 531-535. (Link)
6. Warburton, M. Barefoot running. Sportscience 2000; 5; 1-4.
7. Sinclair J, Greenhalgh A, Brooks D, Edmundson CJ, Hobbs SJ. The influence of barefoot and barefoot-inspired footwear on the kinetics and kinematics of running in comparison to conventional running shoes. Footwear Science 2013: 5, 45-53.
8. Sinclair, J, Hobbs, SJ, Currigan, G, Taylor PJ. A comparison of several barefoot inspired footwear models in relation to barefoot and conventional running footwear. Comparative Exercise Physiology 2013; 9: 13-21.
9. Squadrone R, Gallozzi C. Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. Journal of Sports Medicine & Physical Fitness 2009; 49: 6-13. (PubMed)
10. Bonacci J, Vicenzino B, Spratford W, Collins P. Take your shoes off to reduce patellofemoral joint stress during running. British Journal of Sports Medicine, (In press). (Link)
11. Sinclair J. Effects of barefoot and barefoot inspired footwear on knee and ankle loading during running. Clinical Biomechanics 2014; 29: 395-399. (PubMed)
12. Sinclair J, Atkins, S, Taylor PJ. The Effects of Barefoot and Shod Running on Limb and Joint Stiffness Characteristics in Recreational Runners. Journal of Motor Behavior 2015 (In press). (PubMed)
13. Sinclair J, Atkins S, Richards J, Vincent H. Modelling of Muscle Force Distributions During Barefoot and Shod Running. Journal of Human Kinetics 2015 (In press).
14. Sinclair, J. (2015). Barefoot and shod running: their effects on foot muscle kinetics. FAOJ 2015; 8: 2. (Link)
15. Altman AR, Davis IS. Prospective comparison of running injuries between shod and barefoot runners. British Journal of Sports Medicine, 2015 (In press). (Link)
16. Sinclair J, Hobbs SJ, Taylor PJ, Currigan G, Greenhalgh A. The Influence of Different Force and Pressure Measuring Transducers on Lower Extremity Kinematics Measured During Running. Journal of Applied Biomechanics 2014 30: 166–172. (PubMed)
17. Sinclair J, Edmundson CJ, Brooks D, Hobbs SJ. Evaluation of kinematic methods of identifying gait Events during running. International Journal of Sport Science & Engineering 2011; 5: 188-192. (Link)
18. Delp SL, Anderson FC, Arnold AS, Loan P, Habib A, John CT, Thelen DG. OpenSim: open-source software to create and analyze dynamic simulations of movement. IEEE Transactions on Biomedical Engineering 2007; 54: 1940-1950. (PubMed)
19. Zajac FE. Muscle and tendon: properties, models, scaling, and application to biomechanics and motor control. Critical Reviews in Biomedical Engineering. 1989; 17: 359–411.
20. Delp SL, Loan JP, Hoy MG, Zajac FE, Topp EL, Rosen JM. An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. IEEE Transactions on Biomedical Engineering 1990; 37: 757–767. (PubMed)
21. Almonroeder, T, Willson, JD, Kernozek, TW. The effect of foot strike pattern on Achilles tendon load during running. Annals of Biomedical Engineering 2013; 41: 1758-1766. (PubMed)
22. Sinclair J, Richards J, Shore H. Effects of minimalist and maximalist footwear on Achilles tendon load in recreational runners. Comparative Exercise Physiology 2015 (In press).
23. Mueller-Wohlfahrt HW, Haensel L, Mithoefer K, Ekstrand J, English B, McNally S, Ueblacker P. Terminology and classification of muscle injuries in sport: a consensus statement. British Journal of Sports Medicine 2012; 47: 342-350. (PubMed)
24. Sinclair J. Side to side differences in hamstring kinematics during maximal instep kicking in male soccer players. Movement & Sport Sciences 2015 (In press).